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Research Article

Stress-Strain Relationship of Clay in Dongting Lake Area Based on Three Damage Factors

Qiu-Nan Chen[1,2] **Xiao-Di Xu**[1] **Zhen-Yu Yang**[1] **Bin-Hui Ma**[1] **Wei Hu**[1,2] **Yong-Chao He**[1] **Xiao-Cheng Huang**[1] **and Yong Lei**[1,2]

[1]*College of Civil Engineering, Hunan University of Science and Technology, Xiangtan 411201, China*
[2]*Provincial Key Laboratory of Stability Control and Health Monitoring of Geotechnical Engineering, Hunan University of Science and Technology, Xiangtan 411201, China*

Correspondence should be addressed to Qiu-Nan Chen; qnchen@hnust.edu.cn

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CU test and CD test were performed to capture the stress-strain characteristics of the clay in Dongting Lake area, China. Since the classical constitutive model cannot ideally describe the strain hardening behavior of the clay, an improved constitutive model that involved three damage factors was proposed. The damage first factor D_1, which represents elemental volume strength F, was fitted by the Weibull function. The second and third damage factors D_2 and D_3, which represent the porosity ratio e and the drainage rate P_ε respectively, were fitted by Harris function. The CD test damage model is constructed by D_1, D_2, and D_3. In the CU test, the porosity ratio e is a constant value, and the drainage volume is 0, so that D_2 is constant value and D_3 is 0. Therefore, the CU test damage model of the clay was constructed using the damage first factor D_1. In the end, the accuracy of the proposed CU/CD damage constitutive models of the clay was validated with the experimental results. It is found that the results fitted by the proposed methodology are in good agreement with the experimental results.

1. Introduction

During the design and construction of foundation and geotechnical structures [1–3], the mechanical characteristics of soil are important factors to evaluate the stability of the structures. The mechanical characteristics of soil are described by the stress-strain relationship of soil. The constitutive model of soil is an important research topic in theoretical soil mechanics. In the past few decades, numerous proposals have been made to describe the stress-strain relationship of soil in triaxial tests (i.e., the consolidated undrained (CU) test and the consolidated drained (CD) test) based on elastic-plastic theory or damage theory and influencing factors [4–7].

For consolidated undrained (CU) test, the original plasticity model of clay was improved based on the hypoplastic theory and the CU test of clay [8]. A modified Duncan-Chang model was proposed to describe the stress-strain relationship of frozen sandy clay by Lai et al. [9]. On the basis of the conventional triaxial compression (CTC) and the reduced triaxial compression (RTC), the stress-strain relationship of soft clay was studied by Sun et al. [10]. Isotach elastoplastic (IEP) model in triaxial stress–strain–strain rate space was proposed on the basis of CU experiments on natural soft clay by Yang et al. [11]. Gu et al. conducted triaxial tests with a variable confining pressure (VCP tests) to explore the coupled effects of shear and normal stress in remodeled saturated clay [12].

Regarding the consolidated drained (CD) test, a fractional derivative creep model of clay was proposed to describe the creep properties of clay by Xu and Cui [13]. CD cyclic triaxial tests were carried out to understand the dynamic properties of loess by Wang et al. [14]. A coupled elastic-plastic constitutive function for unsaturated compacted kaolin under consolidation drainage and shear infiltration conditions was presented [15]. Yin et al. proposed the theory of geotechnical strain hardening exponent and verified it by numerous triaxial tests, and the parameters were given physical meanings by means of fractional differentiation [16].

Based on CD tests and CU tests of disturbed and undisturbed granitic saprolites, Elsayed et al. found that soil structure was the most important factor in soil mechanical behavior [17]. Based on true triaxial tests, Zhang et al. proposed an elastic-plastic model to describe the mechanical behavior of structural marine soft soils under general loading [18]. Hasan et al. found that for artificially made clayey soil, the failure of the CU test occurred at a higher strain level than previously theoretical results, while the failure of the CD test occurred at a much lower strain level than previously believed [19]. The stress-strain relationship of chemically damaged rock and soil was studied by Chen et al. [20]. Based on both CU test and CD test of deep-sea clay, a constitutive model considering temperature change was constructed by Sun et al. [21].

Damaged soil mechanics has also been studied for decades [22–30]. The formulation of damage theory originated from Krajcinovic and Silva [31]. Damage theory was applied to frozen soil by Shoop et al. [32]. Ren et al. constructed fractional statistical damage constitutive model of clay based on the improved Harris function [33]. Although a lot of damaged models were proposed to describe the stress-strain relationship of soils, the previous models are mainly under the CU test or CD test, while the relationship between the CU test and CD test is not given. The different mechanical behaviors of clay between CD test and CU test should be studied. In this paper, based on the clay of Dongting Lake area, the CU test and the CD test were carried out, and the CU stress-strain relationship and the CD stress-strain relationship were correlated; then, an improved constitutive model was established. The stress-strain relationship of the clay can be investigated by the proposed constitutive model considering the pore water pressure and the void ratio, but it is insufficient to reflect the deformation law of sand, frozen soil, etc.

The apparatus and testing progress of the triaxial test of the clay from Dongting Lake are introduced in Section 2. Then, an improved constitutive model is proposed in Section 3. Besides, the experimental results are validated with the clay damage constitutive model in Section 4. Finally, the sensitivity of fitting parameters is analyzed in Section 5.

2. Triaxial Test

2.1. Test Instrument. The CD test and the CU test are carried out. The instrument is a GDS stress path triaxial instrument, and the data is collected through a computer. The instrument is shown in Figure 1.

2.2. Soil Parameters. The test soil sample clay is taken from the Dongting Lake area. Various indoor geotechnical tests are carried out on the soil sample. The land taking site can be seen in Figure 2 (the map comes from Tencent Maps). The obtained clay sample parameters are shown in Table 1.

2.3. Test Design. The height of the samples is 76 mm, and the diameter of the samples is 38 mm. Firstly, vacuum saturation is carried out, and the saturation time is not less than two days; then, the samples were saturated for four hours with back pressure of 90 kPa and confining pressure of 100 kPa. Then, observe the B value (specimen saturation indicator value) through the B-check module of the instrument. If the B value does not exceed 0.98, the back pressure saturation needs to be performed again. If the B value exceeds 0.98, the sample is considered to be well saturated. Then, the samples are subjected to isobaric consolidation, and the consolidation is considered complete when the drainage volume during the consolidation process is basically stable. After the completion of consolidation, the shear tests are carried out, and the test parameters are shown in Table 2.

3. Damage Constitutive Model of Clay

There are some constitutive model in rock and soil mechanics [2, 34]. When the damage parameter is not considered, the stress-strain curve is considered as strain hardening type for the pseudotriaxial test of soil [16, 33]. Then, the damage constitutive model of clay conforms to the following formula:

$$\sigma_1 = E v_0^{\beta} \frac{1}{\Gamma(2-\beta)} \varepsilon_1^{(1-\beta)} + 2\mu\sigma_3, \tag{1}$$

where E is the elastic modulus, β is the hardening index, v_0 is the shear rate, μ is the Poisson's ratio, $\Gamma(2-\beta)$ is the gamma function of $2-\beta$, ε_1 is the strain ratio, σ_1 is the principal stress, and σ_3 is the secondary stress.

Among them, the shear rate v_0 can be expressed by the following formula:

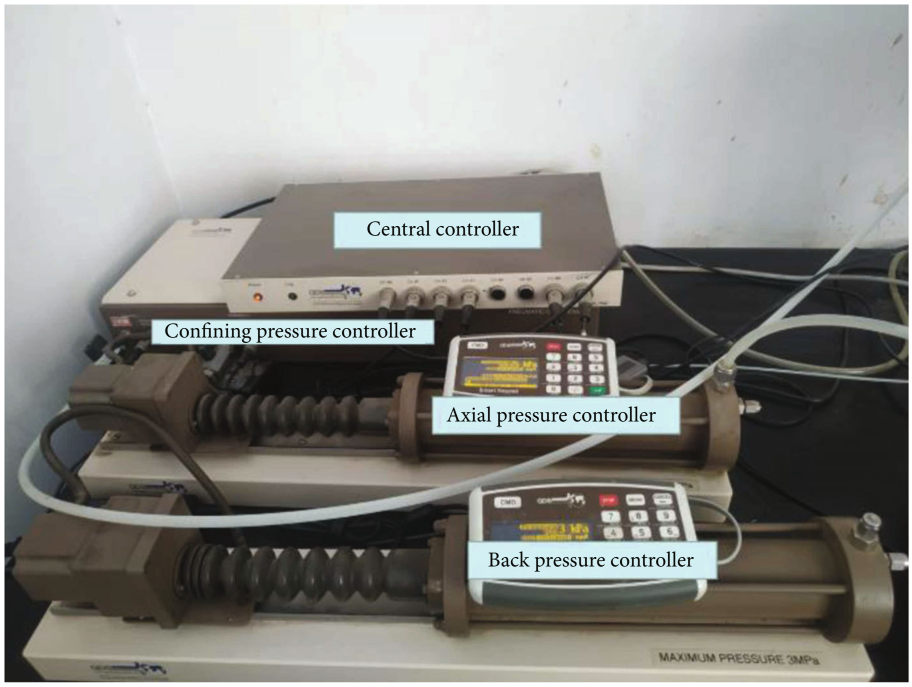
$$v_0 = \frac{v}{h}, \tag{2}$$

where v is the set shear speed and h is the height of the sample.

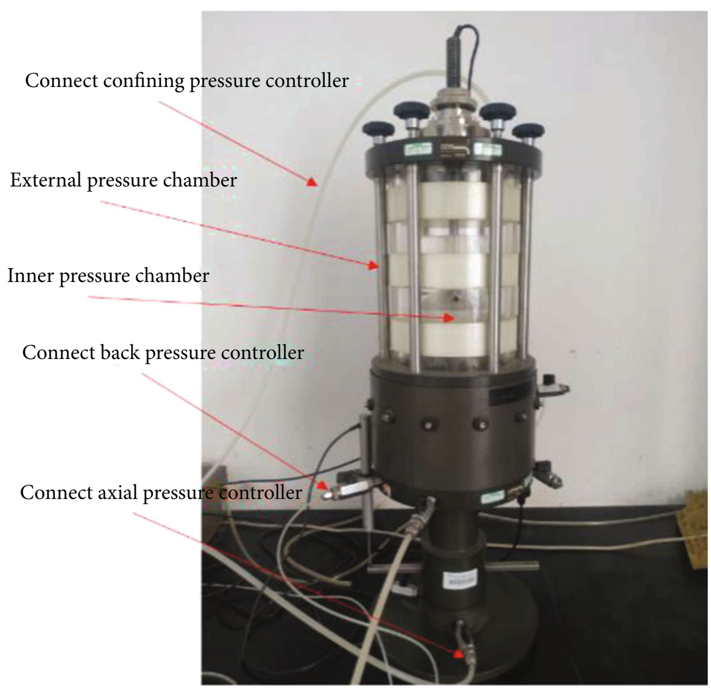
3.1. Three Damage Factors. Comparing the CU test and the CD test, it is found that the difference between them is whether drainage is carried out in the shearing stage, and the drainage is mainly reflected in the change of void ratio and the drainage rate. An increase in void ratio leads to a decrease in soil compaction, and an increase in drainage rate produces an unloading effect.

According to the mechanical properties of soft clay in the Dongting Lake area, a clay failure constitutive model with three damage factors is proposed. The representative elemental volume strength is used as a parameter of the damage factor D_1, the void ratio is used as a parameter of the damage factor D_2, and the drainage rate is considered as a parameter of the damage factor D_3; then, formula (1) can be transformed into the following formula:

$$\sigma_1 = (1-D_1)(1-D_2)(1-D_3) E v_0^{\beta} * \frac{1}{\Gamma(2-\beta)} \varepsilon_1^{(1-\beta)} + 2\mu\sigma_3. \tag{3}$$



(a) Controller



(b) Double pressure chamber

Figure 1: Control system and double pressure chamber.

3.2. Representative Elemental Volume Strength Determined. Based on the Drucker-Prager criterion [35], the following formula can be obtained:

$$F = \alpha I_1 + \sqrt{J_2}, \tag{4}$$

where α represents the element volume intensity parameter, I_1 is the first invariant of the stress tensor, and J_2 is the second invariant of the stress deviator.

Based on the existing research, the D-P criterion matching the M-C criterion is the inscribed circle criterion DP3, and the expression for α in the DP3 criterion is as follows:

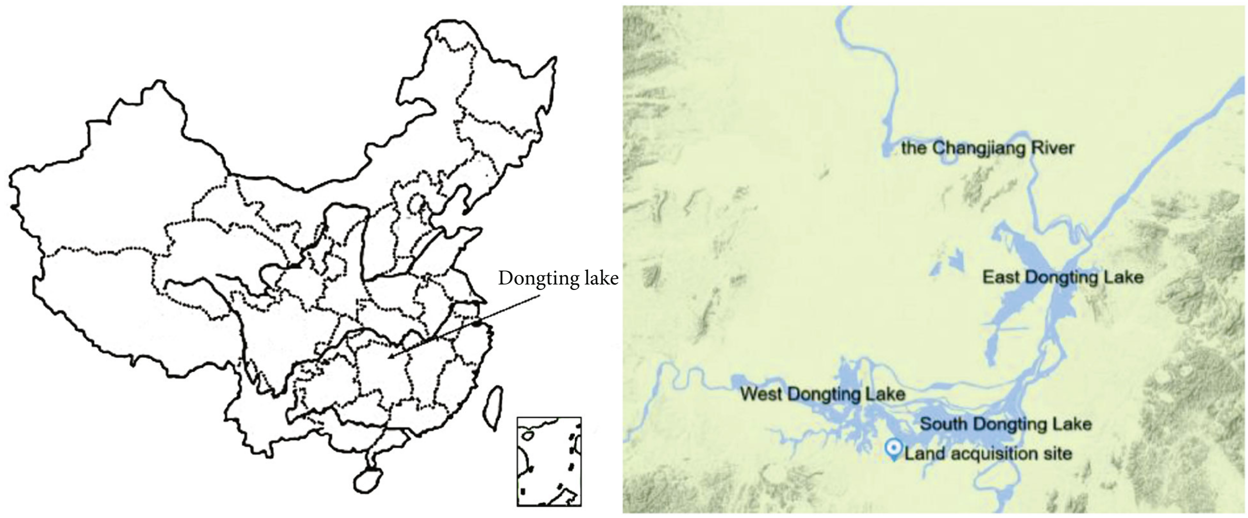


Figure 2: Testing clay collected from Dongting Lake area, China.

Table 1: Basic properties of soft clay in Dongting Lake area.

Moisture content (%)	Specific gravity	Poisson's ratio	Elasticity modulus (MPa)	Liquid limit (%)	Plastic limit (%)	Cohesion (kPa)	Internal friction angle (°)
31.35	2.66	0.31	4.39	33.86	22.23	5.42	25

Table 2: The parameters of test.

Name of test	Back pressure (kPa)	Confining pressure at saturation stage (kPa)	Rate of confining pressure (kPa/min)	Confining pressure during shearing (kPa)	Shear velocity (mm/min)
	90	100	0.833	140	0.075
CD	90	100	0.833	190	0.075
	90	100	0.833	240	0.075
	90	100	0.833	140	0.075
CU	90	100	0.833	190	0.075
	90	100	0.833	240	0.075

$$\alpha = \frac{\sin\varphi}{\sqrt{3}\sqrt{3+\sin^2\varphi}}. \tag{5}$$

According to engineering elastoplastic mechanics [36], the following relation can be known:

$$I_1 = \sigma_1^* + \sigma_2^* + \sigma_3^*, \tag{6}$$

$$J_2 = \frac{(\sigma_1^* - \sigma_2^*)^2 + (\sigma_2^* - \sigma_3^*)^2 + (\sigma_3^* - \sigma_1^*)^2}{6}. \tag{7}$$

In the research of this paper, the nominal stresses σ_1, σ_2, and σ_3 and strain ε_1 can be measured. Since the pseudotriaxial test is performed, $\sigma_2 = \sigma_3$ in this test, and the corresponding effective stress is σ_1^*,σ_2^*, and $\sigma_3^*(\sigma_2^* = \sigma_3^*)$, based on the research of Cao et al. [37]; the equation F can be obtained as follows:

$$F = \frac{\sin\varphi(\sigma_1 + 2\sigma_3)E\varepsilon_1 + \sqrt{3+\sin^2\varphi}(\sigma_1 - \sigma_3)E\varepsilon_1}{\sqrt{3+\sin^2\varphi}\sqrt{3}(\sigma_1 - 2\mu\sigma_3)}. \tag{8}$$

The functional relationship between the damage factor D_1 and the microelement strength F is based on the research of Cao et al. [37], and the Weibull distribution function is used as the constituent equation of the damage factor D_1, and D_1 is as follows:

$$D_1 = 1 - \exp\left(-\left(\frac{F}{c}\right)^d\right). \tag{9}$$

3.3. Pore-Solid Ratio Determined. The specific gravity of the clay and the quality of the clay after drying are obtained through the specific gravity test to determine the volume V_s of the clay in the three phases of the clay. Take the internal size of the saturator as the total volume V. Since the instrument is monitored in real time by the computer, the volume change rate in the whole process can be obtained,

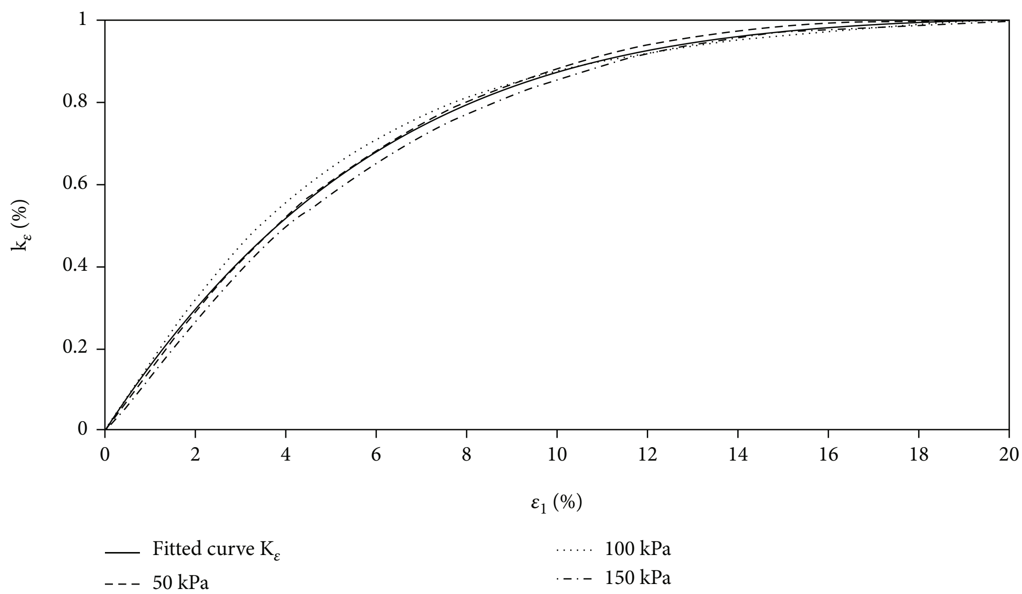


Figure 3: Diagram of axial displacement and relative drainage ratio.

and the volume change at the end of the consolidation process of the triaxial test is taken as V_1. Taking the volume of inhaled water as positive number, this test is a consolidated drained test, and the drainage volume at the end of shearing is taken as V_2. The drainage volume is considered as an equation of axial strain V_ε during shearing. Regarding V_ε, it is expressed by multiplying the relative drainage ratio K_ε of the shearing process by the final drainage volume V_2. From the test data, it can be known that the relationship between K_ε and strain ε is shown in Figure 3; then, K_ε can be expressed by the function fitting of strain ε. The selected K_ε is the average value of K_ε under three confining pressure conditions, among which the values of p_1, p_2, p_3, and p_4 can be obtained by fitting with the MATLAB software.

$$K_\varepsilon = p_1\varepsilon^4 + p_2\varepsilon^3 + p_3\varepsilon^2 + p_4\varepsilon. \quad (10)$$

Then, the pore-solid ratio e can be expressed by the following formula:

$$e = \frac{V - V_s + V_1 + K_\varepsilon V_2}{V_s}. \quad (11)$$

The Harris function is introduced as the constituent equation of the damage factor D_2, which is expressed as the following formula:

$$D_2 = 1 - \frac{1}{1 + me^k}. \quad (12)$$

In this formula, m and k are used as the parameters of this formula, and the void ratio e is used as the main variable. It can be seen from this that the following relationship exists between m and k under the current confining pressure:

Table 3: The fitting model parameters of CU test in clay of Dongting Lake area.

Confining pressure (kPa)	D_2^*	c	d	β	R-square
50	0.656	200	0.172	0.563	0.997 2
100	0.530	400	0.196	0.521	0.996 3
150	0.437	600	0.205	0.486	0.965 9

$$m = \frac{D_2}{(1 - D_1)((V - V_s + V_1)/V_s)^k}. \quad (13)$$

Substituting equations (10) and (11) into (12), the damage factor D_2 can be obtained as an equation of strain ε, and the functional form is as follows:

$$D_2 = 1 - \frac{1}{1 + m((V - V_s + V_1 + (p_1\varepsilon^4 + p_2\varepsilon^3 + p_3\varepsilon^2 + p_4\varepsilon)V_2)/V_s)^k}. \quad (14)$$

3.4. Drainage Rate Determined. During the consolidated drained shearing process, the drainage volume V_ε in the shearing process can be obtained by the relative drainage ratio K_ε of equation (10) and the final shear drainage volume (V_2) obtained in the test process, as shown in the following equation (15):

$$V_\varepsilon = K_\varepsilon V_2. \quad (15)$$

By derivation of V_ε, the drainage rate P_ε during the test can be obtained:

$$P_\varepsilon = \frac{dK_\varepsilon}{d\varepsilon} V_2 = \left(4p_1\varepsilon^3 + 3p_2\varepsilon^2 + 2p_3\varepsilon + p_4\right) V_2. \quad (16)$$

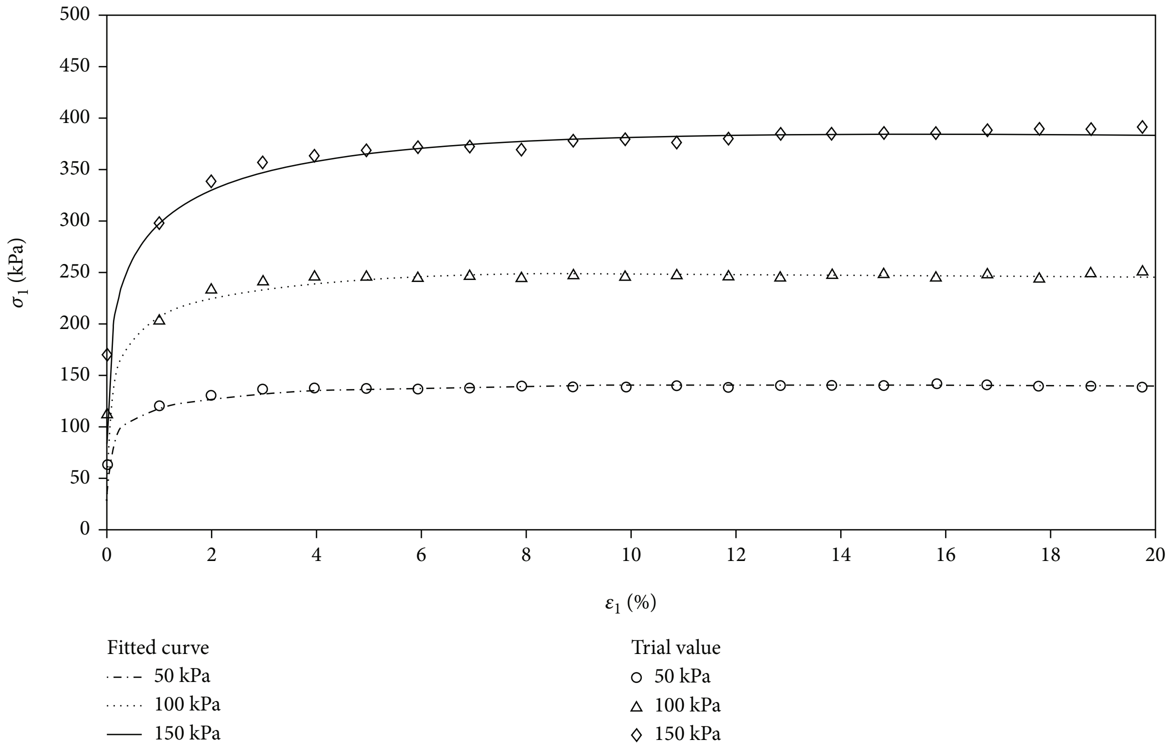


Figure 4: CU stress-strain fitting curve of clay in Dongting Lake area.

During drainage, its damage factor D_3 is constantly changing under the influence of drainage rate P_ε. Using the Harris function to fit its relationship, the following formula can be obtained:

$$D_3 = 1 - \frac{1}{1 + a(P_\varepsilon)^b}. \tag{17}$$

Substitute equation (16) into equation (17) to get the following equation:

$$D_3 = 1 - \frac{1}{1 + a((4p_1\varepsilon^3 + 3p_2\varepsilon^2 + 2p_3\varepsilon + p_4)V_2)^b}. \tag{18}$$

3.5. Damage Constitutive Model of CD Test. To sum up, the following formula can be obtained from formula (3), formula (9), formula (14), and formula (18):

$$\sigma_1 = \left(\exp\left(-\left(\frac{F}{c}\right)^d\right)\right)\left(\frac{1}{1 + m(V_\varepsilon/V_s)^k}\right)\left(\frac{1}{1 + a(P_\varepsilon)^b}\right) * Ev_0^\beta \frac{1}{\Gamma(2-\beta)}\varepsilon_1^{(1-\beta)} + 2\mu\sigma_3. \tag{19}$$

3.6. Damage Constitutive Model of CU Test. During CU test, V_2, drainage rate, and the influence factor are always 0. During the shear process of the consolidated undrained shear test, the pore-solid ratio e is constant due to the water that cannot be condensed. D_2^* represents the damage coefficient. D_2^* is a fixed value during the shearing process under constant confining pressure. The damage constitutive model of CU test can be obtained by damage constitutive model of CD test degenerated; the calculation formula is as follows:

$$\sigma_1 = \left(\exp\left(-\left(\frac{F}{c}\right)^d\right)\right)(1 - D_2^*) * Ev_0^\beta \frac{1}{\Gamma(2-\beta)}\varepsilon_1^{(1-\beta)} + 2\mu\sigma_3. \tag{20}$$

Table 4: The fitting model parameters of CD test in clay of Dongting Lake area.

Confining pressure (kPa)	k	a	b	R-square
50	12.97	0.001 09	0.412 8	0.999 6
100	13.25	0.003 589	0.700 3	0.974 9
150	14.31	0.004 656	0.739 1	0.996 9

4. Test Results Fitted

According to the test results, there is no peak point in the consolidated drainage and CU tests of saturated clay in the Dongting Lake area, which is strain hardening. Therefore, the method of finding the partial derivative of the peak point cannot be used to determine the model parameters. This time, the curve fitting method was used to determine the model parameters. In the curve fitting process, the consolidated undrained curve is first fitted, and then, the consolidated undrained fitting results are substituted into the

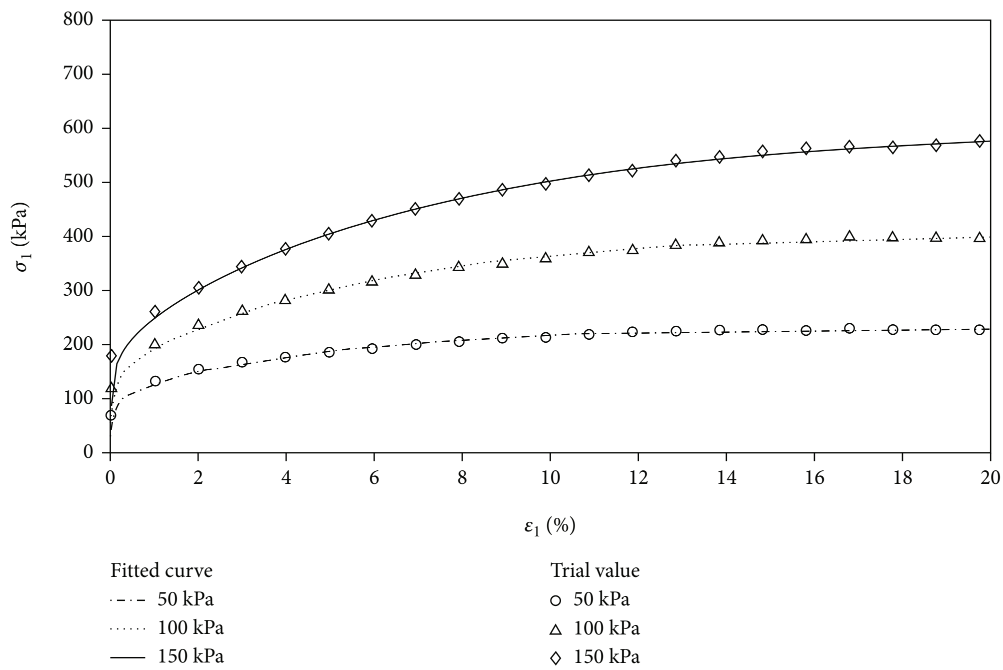


Figure 5: CD stress-strain fitting curve of clay in Dongting Lake area.

consolidated drained formula to obtain the consolidated drained parameters.

4.1. CU Test Results Fitted. According to the data in Table 1, the Poisson's ratio of clay in Dongting Lake area is 0.31, the internal friction angle is 25°, and the elastic modulus is 4.39 MPa. When fitting, the parameter c in the Weibull distribution is taken as a fixed value. The parameters of the fitting analysis model are shown in Table 3, and the curve is shown in Figure 4.

R-square is called the coefficient of determination of the equation. The closer the value of R-square is to 1, the higher the fitting degree of the mathematical model. This value is calculated by MATLAB. It can be seen from Table 3 that the R-square is greater than 0.95, and the fitting effect is good. It can be seen from Figure 4 that in the consolidated undrained test, the strain of 0% to 2% can be divided into the early loading stage, and the strain of 2% to 20% is the later stage of loading. According to the fitting results, with the increase of confining pressure, the damage coefficient D_3^* caused by pores gradually decreases, which is the same as the change trend of clay porosity. According to the research of Hu and Cao, the hardening exponent is $(1-\beta)$, which reflects that the nonlinearity of the material stress-strain curve increases with the increase of the confining pressure, which means that the nonlinearity of the clay increases gradually with the increase of the confining pressure [38]. Gradually move closer to the ideal solid material properties. The equation parameter c is a proportional parameter taken according to the confining pressure, and the parameter d increases gradually with the increase of the confining pressure.

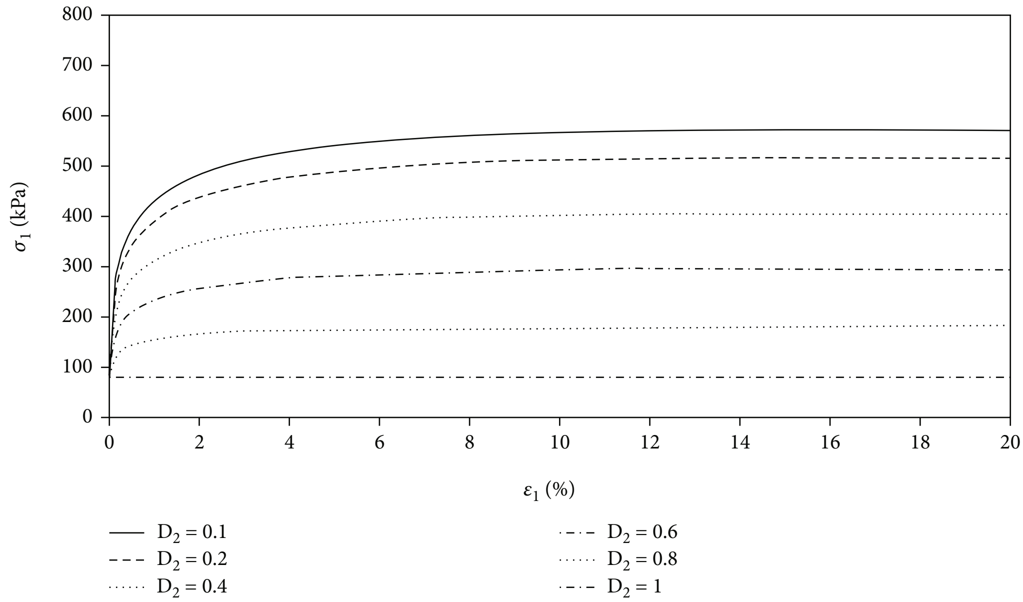
4.2. CD Test Results Fitted. According to the fitting results in 4.1, the parameters are substituted to fit the consolidated drained model. Since the value of D_2 has been obtained during the consolidation undrained fitting process, m can be represented by k. The analytical model parameters are shown in Table 4, and the curve is shown in Figure 5.

It can be seen from Table 4 that the R-squares are all greater than 0.97. Compared with the CU test images, the strain of 0% ~2% can be divided into the early stage of loading, the strain of 2% ~15% can be divided into the middle stage of loading, and the strain of 15% ~20%. It is divided into the later stage of loading, and it can be seen that the overall trend is that the tangential elastic modulus decreases rapidly in the early stage of loading, and the tangential elastic modulus decreases slowly in the middle stage of loading, and its tangential elastic modulus gradually approaches 0 at the end of loading. It can be seen that with the increase of the confining pressure, the parameters k, a, and b are gradually increasing, but the increasing trend is not linear, indicating that there is a certain functional relationship between the parameters and the confining pressure.

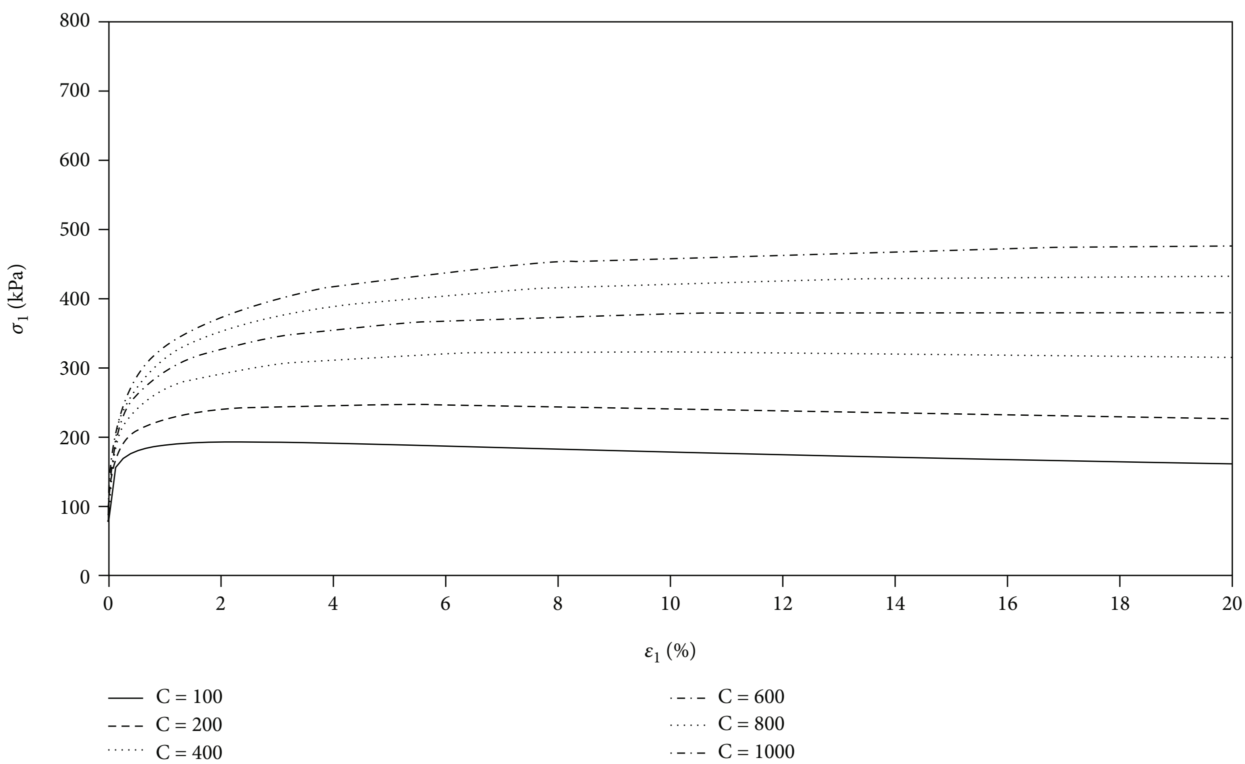
5. Parametric Analysis

5.1. CU Parameter Analysis. The 150 kPa confining pressure of the consolidated undrained test is analyzed by following the principle of single variable. The four parameters of the consolidated undrained test are shown in Figure 6.

It can be seen from Figure 6 that in the CU model of this paper, the value of D_2 ranges from 0 to 1. As D_2 increases, σ_1 decreases. When D_2 is 0, it is a constant value; the parameter

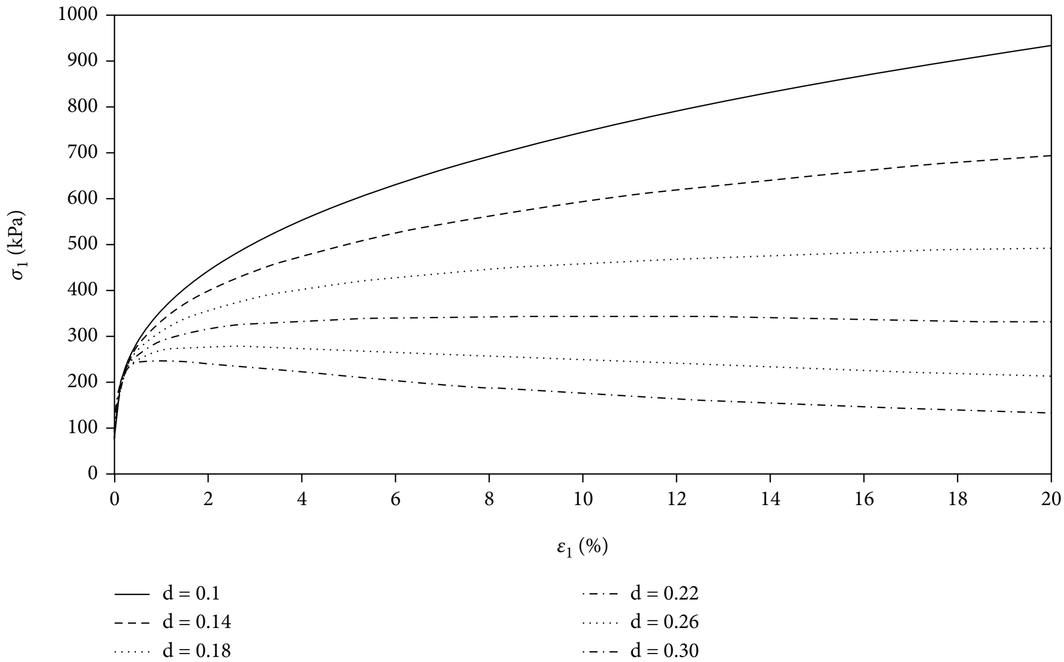


(a) Influence curve of parameter D_2^*

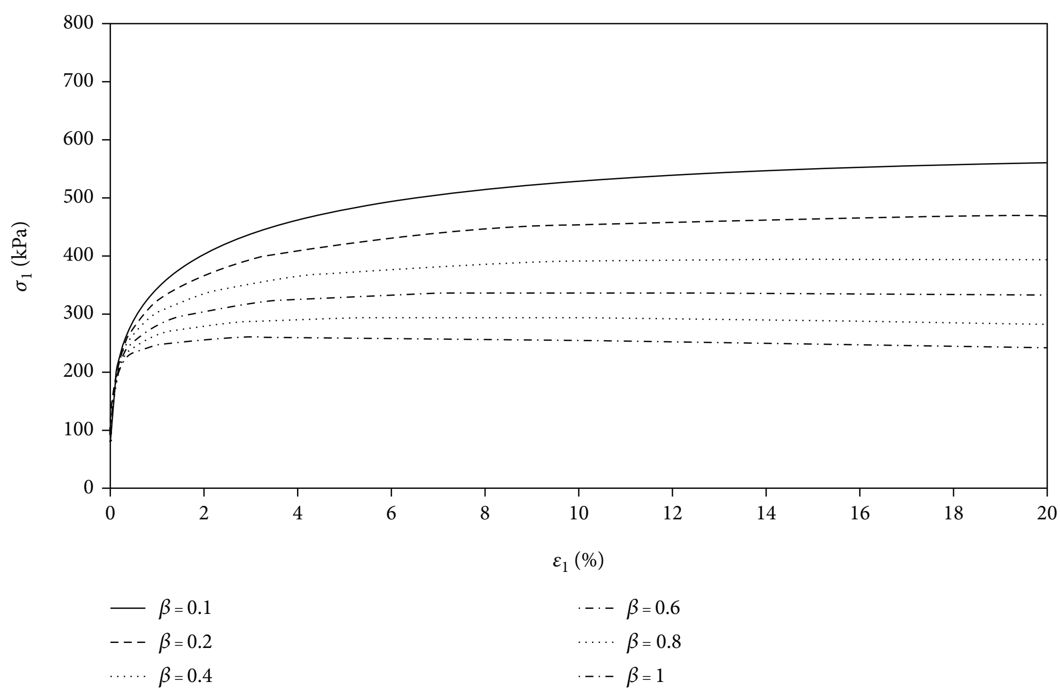


(b) Influence curve of parameter c

FIGURE 6: Continued.



(c) Influence curve of parameter d

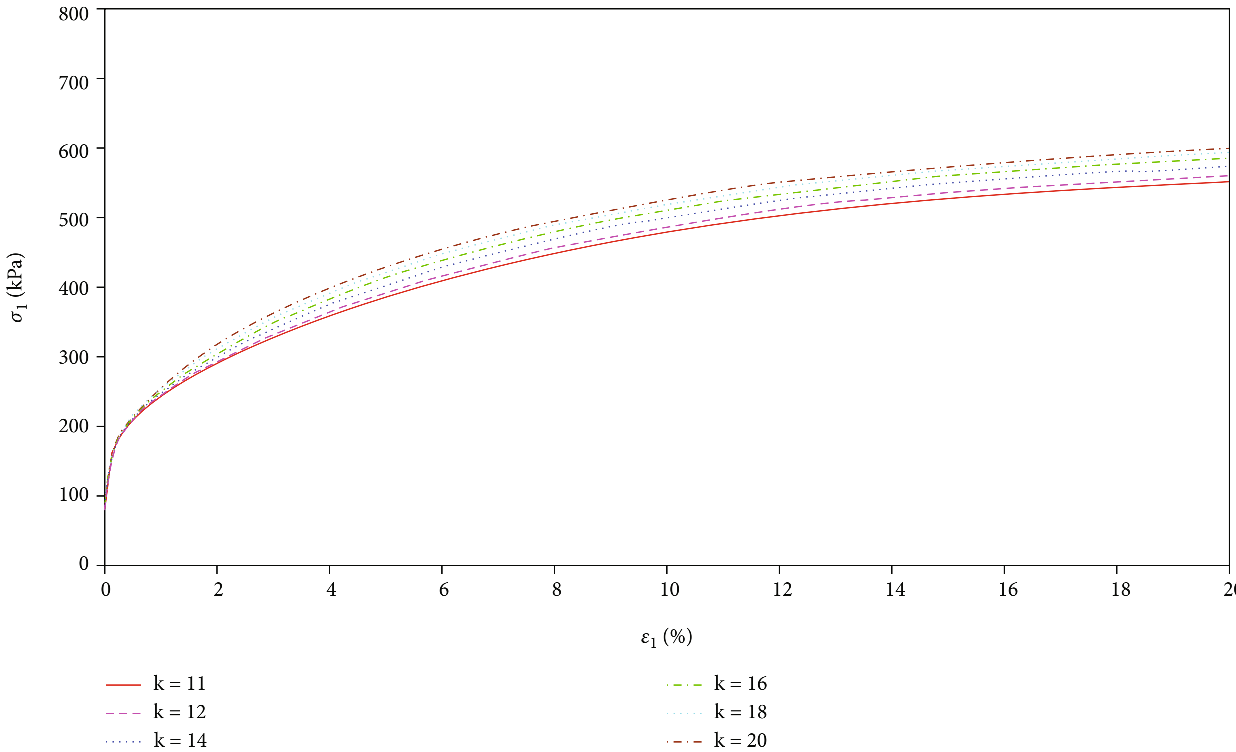


(d) Influence curve of parameter β

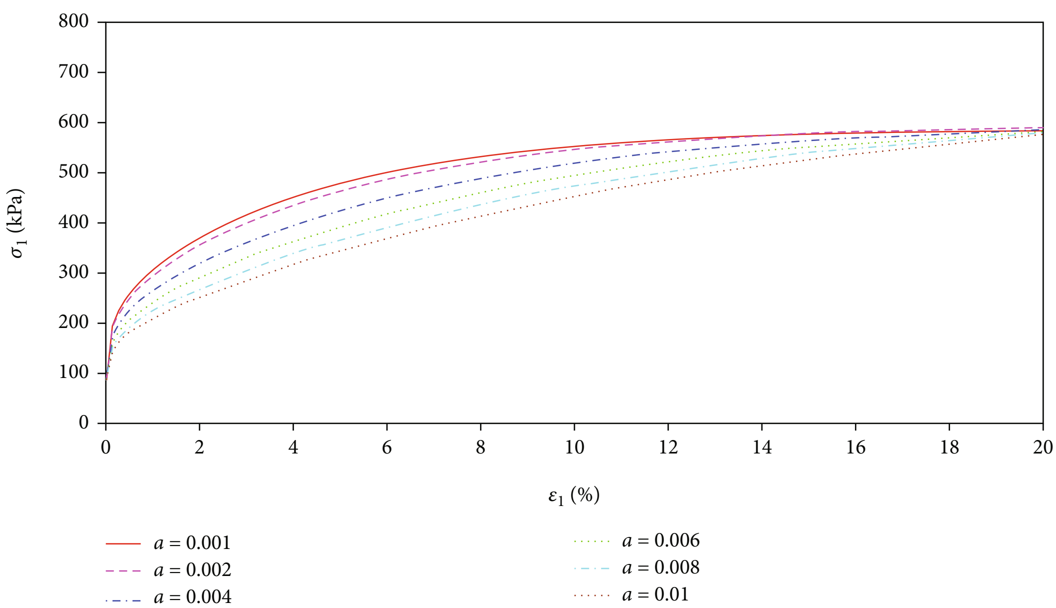
Figure 6: Cu stress-strain curve under the influence of a single variable.

c increases. When it is large, the maximum value of σ_1 gradually increases, which effectively reflects the damage of the clay structure after failure; the parameter d mainly affects the curve shape of the damage constitutive model. There is an inflection point nearby, and the subsequent change trend changes accordingly; the influence of the parameter β has a certain correlation with the strain hardening index, and its value ranges from 0 to 1; $(1-\beta)$ is the hardening index, and with the increase of β, the $(1-\beta)$ gradually decreases; its hardening index gradually decreases, and its nonlinearity gradually increases.

5.2. CD Parameter Analysis. The 150 kPa confining pressure of the consolidation-drained test is analyzed by following the principle of single variable, and the three-parameter law of consolidated drained is shown in Figure 7.

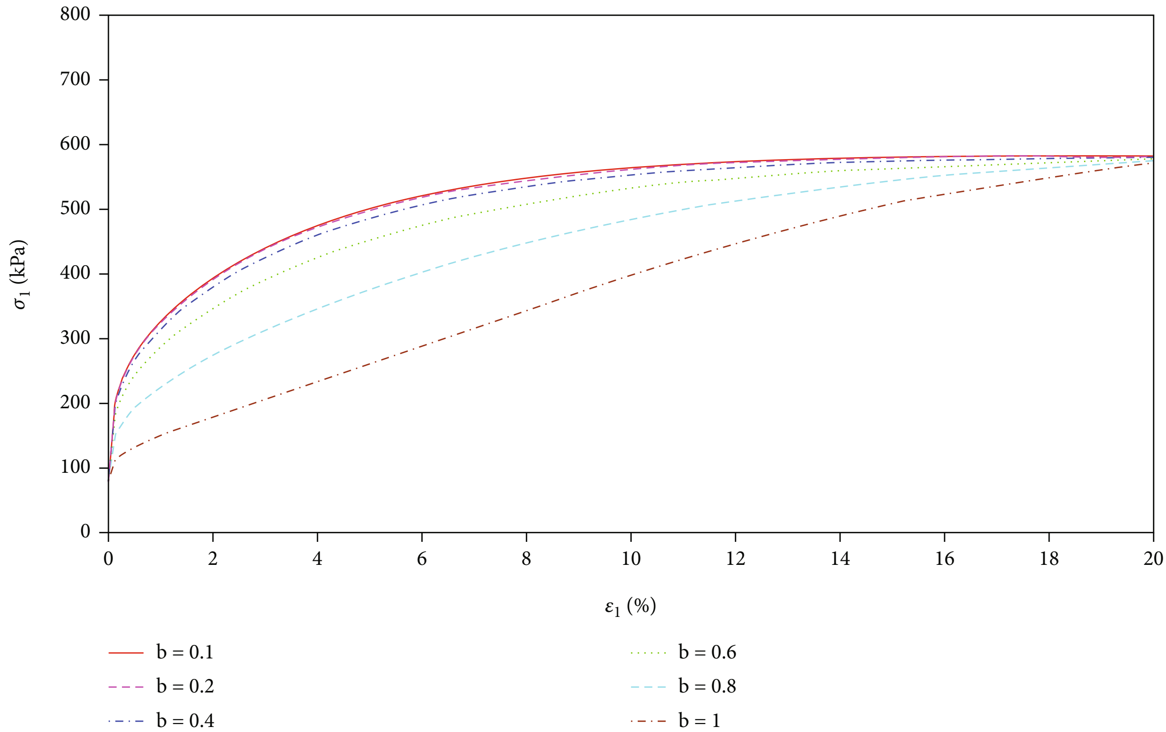


(a) Influence curve of parameter *k*



(b) Influence curve of parameter *a*

Figure 7: Continued.



(c) Influence curve of parameter b

Figure 7: CD stress-strain curve under the influence of a single variable.

It can be seen from Figure 7 that the parameter k mainly affects the final shear stress, and it has no effect on the shape of the curve; in formula (19), the parameter k mainly affects the damage factor D_2, which is related to the final shear stress. With the increase of k, the final shear stress increases gradually, which is consistent with the fitting results. Both parameter a and parameter b have an effect on the stress path but do not have a significant effect on the final shear stress, but there are certain differences in the scope of their influence. The parameter a mainly affects the changes before and during the loading period. With the increase of b, the degree of bending gradually increases, and the parameter b mainly affects the change in the whole loading process. It is more obvious than the parameter a; comparing the parameter a and the parameter b, it can be seen that the initial change of the parameter a has a more obvious influence on the curve than the later stage, and the later stage of the parameter b change has a more obvious influence on the curve than the initial stage. The binding energy of parameters a and b fully reflects the effect of drainage rate on clay shear stress in CD test.

6. Conclusions

Taking into account the differences in volume change, drainage rate change, and microelement strength between the CD and CU tests in the shear phase, a new intrinsic model was developed based on the existing geotechnical damage intrinsic model. It can be concluded as follows:

(1) CU tests and CD tests were carried out, and data were collected for clays in the Dongting Lake area. It was found that the internal drainage rate of the samples during shear in the CD test was consistent, with a gradual increase to one and a decreasing rate of increase, and the relationship between the relative drainage rate and axial strain during shear in the CD test was determined

(2) Considering the drainage volume and drainage rate during the shear process of the CD test, the constitutive model of three damage factors that can fully reflect the CD test is established. This equation is simplified to obtain a damage constitutive model that can reflect the CU test. The damage constitutive model of the clay in the lake area was fitted, and the fitting results were basically consistent with the test results, which verified the feasibility of the CU/CD damage constitutive model proposed in this paper

(3) The parameters D_2^*, c, d, and β are analyzed according to the CU damage constitutive model, and the shape of the influence curve of damage constitutive model of clay is determined. The parameters a, b, and k are analyzed according to the CD damage constitutive model, and it is determined that the parameter k has a small influence on the final shear stress. Parameters a and b do not affect the final shear stress but only affect the stress during the shearing process

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (Qiu-Nan Chen).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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